

Technical Comment

DEFORMATION LAMELLAE IN QUARTZ

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Deformation Lamellae in Quartz

Recent articles by Carter (1), French (2), and Greenwood (3) on deformation features in quartz, insofar as these are attributed to development by shock-waves, have, in my opinion, both clarified certain points of disagreement and added to misunderstandings in the use of these features as evidence of meteorite impacts. Carter (4) concludes that basal $\{0001\}$ lamellae in quartz can serve as an indicator of a shock event. French (5) states that the high frequency (up to 60%) of the $\{10\bar{1}3\}$ feature, rather than its actual presence, is the critical factor in its value as a shock criterion. Greenwood (6) contends that orientation parallel to $\{0001\}$ and $\{10\bar{1}3\}$ are not necessarily "unique and sufficient criteria for shock metamorphism induced by meteorite impact."

I have compared the characteristics of these planar features in quartz from a variety of rocks subjected to shocks generated by nuclear and chemical explosions with shocked rocks from numerous meteorite impact structures (7). It is clear that certain types of microdeformation in quartz and other minerals, best seen under the petrographic microscope, are common to these two categories of shocked rocks and, furthermore, have not been reported from unshocked rocks deformed by tectonic or volcanic forces. Hence, these microdeformation types, including the so-called planar features in quartz, appear to be unique indicators of the action of intense shock pressures (> 100 kilobars).

Drawing from my previous studies and one currently in progress, I have concluded that several points raised by Carter, French, and Greenwood are in need of further clarification. In particular, the current study, that of shocked quartzites present as rock fragments in alluvium during the 100 kiloton Sedan nuclear explosion (8), provides an important insight into the use of planar features in

quartz as one indication of a shock event. Owing to inevitable delays in publication, at a time when many investigators are seeking firm criteria for recognition of impact structures, I wish to preview here several results of this quartzite study as they apply to the conclusions of Carter et al. regarding deformation lamellae in quartz.

1) The test first suggested by Carter (9), involving the use of phase contrast illumination, by which tectonic deformation lamellae can be distinguished from shock-induced planar features, receives ample support from examination of several Sedan quartzite samples. Tectonic lamellae ^{are present} in unshocked quartzites from source outcrops near the Sedan crater. Their most frequent orientations, in terms of the angle between their poles and the c-axis of each host quartz grain, range from 15 to 25°. Orientations parallel to {0001} (basal lamellae) are rare. These tectonic lamellae are also present in grains of sample 1067-65 in co-association with planar features (Fig. 1a; Fig. 2a) but both types of planar elements are almost never evident in the same grain. As Carter notes (10), in phase contrast the tectonic lamellae generally show a single dark border on one side whereas the planar features are bounded by dark borders on both sides. In this sample, the orientation of the majority of planar features is ^{within ± 5° of} very similar to that of the lamellae in unshocked equivalents and some of the planar features represented by the maximum interval at 16-18° are probably pre-shock deformation lamellae. However, in phase contrast many of these planar elements appear to be shock-produced features, suggesting that as they develop they may sometimes follow pre-existing lamellae zones that localize the actual deformation.

2) While Carter's conclusion that basal lamellae are indicators of impact is no doubt valid for the cases he examined, it is my observation that these lamellae are rare to absent in most shocked rocks. At most, only 1 to 3% of the planar features I have measured in explosion- or impact-shocked rocks fall within the interval 0-6°, for which a {0001} orientation can be assumed. The {0001} form is especially rare

in most of the shocked quartzites, even in samples which show only a low density and small average of sets of planar features (e.g., sample 1067-63). The only notable exception is sample A-19 in which ^{near} basal lamellae constitute 15% (Fig. 2c). Because $\{0001\}$ is generally the first planar feature to appear (11), it has been assumed that this orientation tends to develop in the rock region enveloped by the expanding shock front within which the pressures are just above the dynamic elastic limit for the material. In terms of total volume of shocked rock, this region includes only a few percent ($< 5\%$) of the material affected. Although diagnostic, these basal lamellae are volumetrically far less useful as a shock indicator than more frequent forms such as $\{10\bar{1}3\}$, $\{22\bar{4}1\}$, and $\{10\bar{1}2\}$.

3) Robertson et al (12) have shown that as shock damage to mineral grains increase, presumably as a function of increasing shock pressures, the frequency distribution of the different crystallographic forms to which the planar features are indexed will shift systematically. Thus, at lower pressures, $\{10\bar{1}3\}$ is the most abundant but, as pressures rise, such forms as $\{22\bar{4}1\}$ and $\{10\bar{1}2\}$ become common, so that the dominance of $\{10\bar{1}3\}$ continually decreases. At the same time, the number of different sets of features (of all forms) and the density and spacing of these sets in individual grains will also increase as this frequency distribution varies with rising pressures. The data presented in the Figure 2 histograms, arranged in a sequence presumed to represent increasing shock damage (13), strongly confirm the stages of deformation proposed by Robertson et al.

Both French and Greenwood (14) refer to the dominance of lamellae or planar features in the histogram class intervals near 23° as a decisive characteristic of shocked quartz. Greenwood (15) particularly states "that impactites (16) appear to be distinguished [from geotectonically deformed rocks] by the relative absence of lamellae at angles which deviate greatly from 0 to 23° ." While this may be true for quartz shocked over a limited pressure range, it is obvious from inspection of the Figure 2 histograms that this does not hold for quartz shocked at higher pressures.

Thus, measurements of planar features in the more intensely shocked quartzites (Figs. 2b and 2f) plot as broad bell-shaped curves which tend to resemble some plots obtained by Carter (17) for tectonic lamellae and fracture orientations, except that his maxima or peak values for c-axis \wedge pole angles do not normally coincide with those for shocked rocks. The key distinctions however are the much greater number of sets and the spacing of planar features, along with their double dark-bordered appearance in phase contrast lighting, which are characteristic of the shocked quartz. As far as I know, no one has ever reported anything close to an average of 5 sets of deformation lamellae, spaced as closely as 10 microns (Fig. 1b), in any tectonically stressed rock; not even rocks loaded experimentally by "rock squeezers" develop such striking microdeformational features as those observed in the Sedan quartzites and in rocks showing equivalent damage from such impact structures as the Ries Kessel, Brent, West Hawk Lake, and Gosses Bluff (18). Also, intimate association of remnant planar features with isotropic pseudomorphs (thetomorphs [19]) of ^{Sedan} quartz (Fig. 1d) and noted also in quartz from presumed impact crater sites, is likewise a phenomenon totally unknown from unshocked rocks of any kind.

4) The x-ray diffraction asterism (20) data added to Figure 2 provide another valuable criterion for distinguishing shock-deformed from tectonically-stressed quartz. Asterism line lengths for unshocked but tectonically-stressed Sedan quartzite equivalents range between 1.1 and 1.4 μ m. These appear as spots or slightly elongated lines on the x-ray diffraction film. The line lengths for strongly shocked quartzite samples are notably greater and there is no overlap in values with the unshocked (or slightly shocked) samples. This corresponds to the observations by Dacheville et al. (21), who contend that in nearly all cases asterism values for shocked and tectonic quartz fall into two distinctly separate groups. The general correlation between increasing asterism and the increased number and density of

planar feature sets indicated by the data in Figure 2 is probably not coincidental. The planar feature distribution and density, as an indicator of shock damage, may also indirectly represent an index for the extent of fragmentation of individual crystals into micropaggregates (polygonization) which in part controls the degree of asterism in a deformed crystal.

In sum, I should like to reiterate the caution made by other workers that, while it appears that tectonic deformation lamellae and shock planar features belong to two distinctly different "populations", we have not yet accumulated enough critical observations to set forth precise distinguishing characteristics applicable to all possible cases. As the new field of shock metamorphism continues to grow with each investigation, we may expect eventually to agree upon a group of definitive and well-established criteria for recognizing meteorite impact structures.

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References and Notes

1. N. L. Carter, Science 160, 526 (1968)
2. B.M. French, Science 160, 905 (1968)
3. W.R. Greenwood, Science 158, 1180 (1967); Science 160, 906 (1968)
4. N.L. Carter, Science 160, 526 (1968); Amer. J. Sci. 263, 786 (1965)
5. B.M. French, Science 160, 905 (1968)
6. W.R. Greenwood, Science 160, 906 (1968)
7. N. M. Short, in Shock Metamorphism of Natural Materials, B.M. French & N. M. Short, Eds. (Mono, Baltimore, in press)
8. The Sedan event produced a 340 meter wide crater by detonation of a nuclear device buried 194 meters in alluvium at the Nevada Test Site in July 1962.
9. N. L. Carter, Amer. J. Sci. 263, 786 (1965)
10. N. L. Carter, Amer. J. Sci. 263, 786 (1965)
11. P. M. Robertson, M.R. Dence, and M. A. Vos, in Shock Metamorphism of Natural Materials, B.M. French & N.M. Short, Eds. (Mono, Baltimore, in press)
12. P. M. Robertson, M.R. Dence, and M. A. Vos, ibid.
13. Shock damage is here presumed to increase as the number and density of planar feature sets increases and birefringence decreases; peak pressures given in Fig. 2 are estimates only but are based indirectly on criteria and associated peak pressure values given by E.C.T. Chao and by F. Horz in articles in Shock Metamorphism of Natural Materials, B. M. French & N.M. Short, Eds. (Mono, Baltimore, in press).
14. B.M. French; W.R. Greenwood, Science 160, 905 (1968)
15. W.R. Greenwood, Ibid.
16. The term "impactite" was first applied by V.E. Barnes, Univ. Texas Publ. 3945 (1939) and later by E.C.T. Chao and others to "glassy" rock fragments found at several meteorite craters (e.g., Meteor Crater, Ariz.); as applied by Carter, Am. J. Sci. 263, 786 (1965) and Greenwood, Science, 160, 906 (1968) to shock-damaged crystalline rocks, "impactite" is incorrectly used.
17. N.L. Carter, Science 160, 526 (1968)
18. N.M. Short and T.E. Bunch, in Shock Metamorphism of Natural Materials, B.M. French & N.M. Short, Eds (Mono, Baltimore, in press)
19. This term, derived from the Greek thetos, meaning adopted, and morphe, meaning form, was first proposed by E.C.T. Chao, Science 156, 192 (1957)

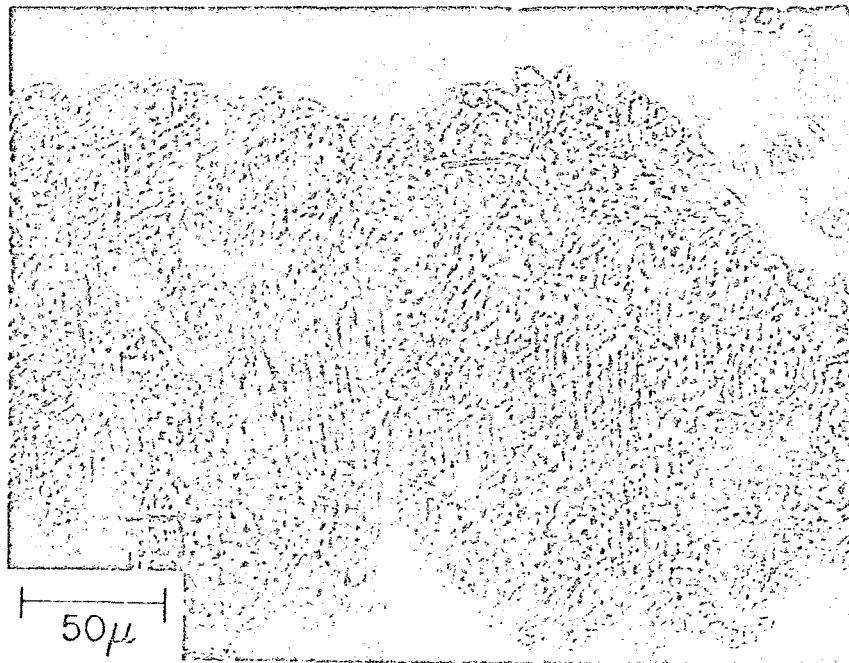
20. F. Dacheille, E.P. Meagher, and V. Vand, Geol. Soc. Am. Spec. Paper 82, 40 (1964)
21. F. Dacheille, P. Gigl, and P.Y. Simons, in Shock Metamorphism of Natural Materials,
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Figure 1 Captions

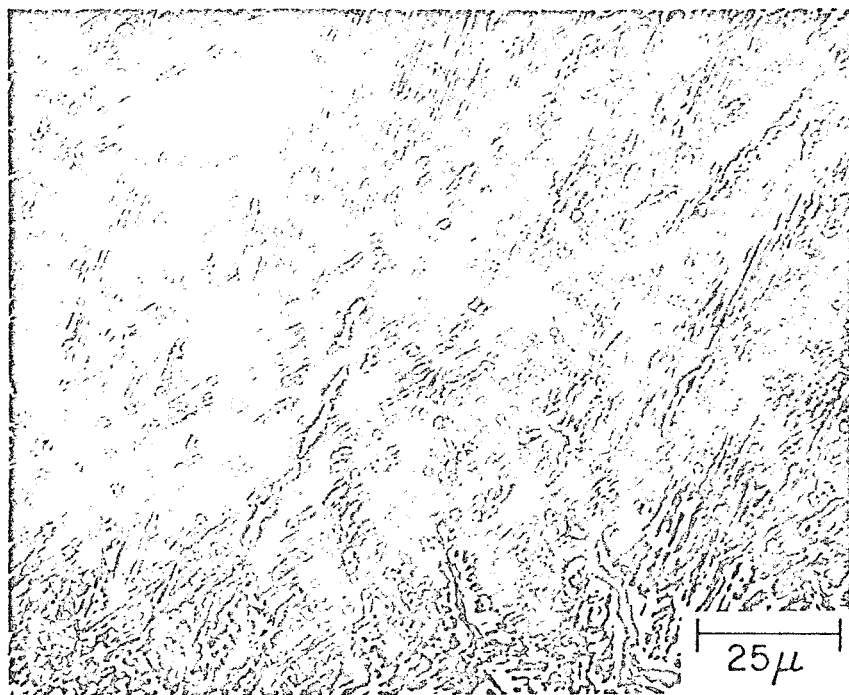
- 1a: Single quartz grain from Sedan sample 1067-65 showing shock-induced NE fractures and a set of $\{10\bar{1}3\}$ planar features trending NNW, both associated with a NNE set of decorated deformation lamellae of presumed tectonic origin; this sample experienced (estimated) shock pressures between ⁷⁵100 and 150 kb. Crossed nicols.
- 1b: A single quartz grain from sample 767-3, estimated to have undergone shock pressures in excess of 250 kb, in which the entire grain has been cut by three visible sets of planar features; two other sets are discernible when the grain is rotated on a universal stage. Plane polarized light.
- 1c: Close-up of part of a large grain from sample A (displaying shock damage similar to 767-3); two prominent sets of planar features (NNE and ENE) are evident along with an E-W set near the bottom of the photo and a poorly developed NNW set on the right. Crossed nicols.
- 1d: A group of quartz grains transformed by shock in excess of 300 kb. to theomorphs (isotropic SiO_2 pseudomorphic after quartz); two sets of planar features are preserved in the "glassy" grain in the center; tiny bubbles indicate incipient vesiculation. Plane polarized light.



1067-66



767-3



A



1067-79

Figure 2 Caption

2: A series of histograms expressing the percent frequency of angles (3° class intervals) between the c-axis of individual quartz grains and poles normal to sets of planar features within these grains, as determined by stereonet plots, for samples of Sedan quartzite arranged in a sequence (a to e, upper left to lower right) representing increased shock damage. Thus, 1067-65 experienced an estimated 75 - 100-kb whereas 1067-97 was subjected to pressures probably above 300 kb. Both birefringence and index of refraction begin to decrease in 767-3; some individual grains in 1067-97 show partial conversion to the isotropic state as their birefringence approaches $\Delta = 0.002$. The ratio recorded for each sample denotes the average number of planar feature sets per grain, as calculated by dividing the total number of sets measured by the number of grains examined. The percentage value underneath represents the number of grains in a total of 100 examined on the universal stage which contain any discernible planar features. The underlined number on the upper left of each histogram is a "Concentration Factor" obtained as follows: Assuming the c-axis \wedge pole poles angle has been measured to $\pm 5^\circ$, the $\{10\bar{1}3\}$ form at 23° would likely be identified with the distribution between $18 - 28^\circ$; an interval arbitrarily selected between $15 - 30^\circ$ is considered to include all $\{10\bar{1}3\}$ sets; the cumulative frequency percentage for this interval is summed and then divided by 16.7% (the percentage assigned to $15/90^\circ \times 100$ if the planar sets are assumed to distribute in equal proportions over all angles) to produce the concentration factor. Vertical dashed lines drawn from specific values on the abscissa designate the c-axis \wedge set pole angles for the following crystallographic forms: $0^\circ = c \{0001\}$; $23.5^\circ = w \{10\bar{1}3\}$; $32.4^\circ = d \{10\bar{1}2\}$ or $\pi \{01\bar{1}2\}$; $47.7^\circ = s \{11\bar{2}2\}$; $51.8^\circ = r \{10\bar{1}1\}$ or $z \{01\bar{1}1\}$.

$65.5^\circ = s \{11\bar{2}1\}$; $76.5^\circ = \{22\bar{4}1\}$; and $82.0^\circ = x \{51\bar{6}1\}$. The number in parenthesis refers to the measured length (in mm.) of a spot or line on film that defines the degree of asterism (20) for the 12.15° 2θ reflection (d spacing of 3.35 Å) obtained by x-ray diffraction analysis of single unoriented, rotating grains exposed for 6 hours in a beam of Mo K_α radiation; each value represents the average of values from two grains.

SEDAN QUARTZITES

